Effect of reinforcement volume fraction on the mechanical properties of the Al-SiC nanocomposite materials

Effect of reinforcement volume fraction on the mechanical properties of the Al-SiC nanocomposite materials

AKM Asif Iqbal[1], Norul Amierah

Faculty of Manufacturing Engineering, University Malaysia Pahang, 26600, Pekan Pahang, Malaysia

Corresponding author: asifiqbal@ump.edu.my

Abstract. Particle reinforced metal matrix composites (MMCs) has emerged as one of the potential materials for structural application due to their superior mechanical properties. However, these MMCs have poor damage tolerance due to their low fracture toughness. The volume fraction of reinforcement plays a significant role to improve the overall strength of the MMCs. In this research, Al matrix composites reinforced with three different volume fraction of the SiC nanoparticles were fabricated by a powder metallurgy process and the effects of volume fraction on the mechanical properties of the Al-SiC nanocomposite was investigated. The samples were prepared with 200 kN compaction load and 600°C sintering temperature. Subsequently, their mechanical testing was carried out. The density and hardness of the samples were investigated. Moreover, the microstructure of the nanocomposites was examined by optical microscope. The results showed that the high volume fraction reinforced nanocomposite exhibited better microstructural feature and high hardness as compared to the low volume fraction reinforced nanocomposite. Therefore, the high volume fraction reinforced nanocomposite can be a potential material to use in the brake disc of the automobile.

1. Introduction

Nowadays, metal matrix composites (MMC) become attractive materials due to their superior properties and potential to use in many applications such as automotive and aerospace industries. The unique mechanical properties such as light weight and high elastic modulus made a considerable interest in these composites to use in the structural applications. These composites also possess high stiffness, strength-to-weight ratio and isotropic properties, superior in general to those of conventional alloys [1-3].

Although MMCs have many advantages, however, they also have poor ductility, low fracture toughness and poor low-cycle fatigue properties [4–6] that affect their overall strength and limit their applications. The mechanical properties of MMCs are directly related to their microstructural features such as the type of reinforcement, matrix/reinforcement interfaces, dislocations, etc. It has been observed that the overall strength of the MMCs is generally affected by the two main parameters related to the reinforcement, the volume fraction and the size of the reinforcing elements. The particle reinforced composites exhibit superior microstructural control over fibre reinforced composites [7] and SiC particles have been widely used reinforcement materials due to their superior high-temperature mechanical properties, high wear resistance and low cost [8-9]. Previous research showed that the increase in volume fraction significantly increase the mechanical properties of the composites. Lloyd [10] used micro-sized particles to increase the volume fraction of the reinforcement and found

increased elastic modulus of the composite. Moreover, as the volume fraction of particles is increased, tensile and yield strengths generally increase, and ductility and fracture toughness decrease [11,12]. Lee et al. [13] have investigated the effect of porosity, volume fraction and size of silicon carbide particles on the abrasion resistance in aluminium alloy 6061 matrix composites fabricated by powder metallurgy.

They found that the abrasion resistance of the composites increased as the amount of SiC increased. Cerit et al. [14] also observed that the hardness value of the composite increased as the volume of the reinforcement increased. All these above research used large micro-sized SiC particles to increase the volume fraction of the reinforcements as well as to increase the strength of the composite. However, the large ceramic particles are prone to cracking during mechanical loading, leading to premature failure [15]. Thus, the desired mechanical properties are difficult to achieve and the application of MMC in the real service condition is significantly hindered. Iqbal et al. [16] have investigated the fracture mechanism of particle reinforced MMCs and found that the particle fracture and the interface debonding of particle/matrix are the major causes of the failure. The crack develops in the vicinity of particle-matrix interface and propagates through the interface and on the particle [17,18].

Therefore, one solution to increase the crack initiation life and to obtain the desired mechanical properties could be to decrease the particle size from micrometer to nanometer level. Because below a critical size, particle no longer fracture and the crack cannot develop in the interface as the interface region is very small [19]. However, to do so, the volume of the nanoparticle needs to be increased to maintain the desired volume fraction of the reinforcement. Moreover, to achieve superior mechanical properties of nanocomposites, the particle distribution must be uniform within the metal matrix [20]. But, the homogeneous distribution of nanoparticles in the matrix is very difficult to maintain and becomes a major challenge of Al-SiC nanocomposite fabrication. Researchers used many different methods to fabricate the MMCs and found interesting results. Although the melting and casting route is cost effective, there are problems with poor wettability between the ceramic reinforcements, the inhomogeneous distribution of reinforcements and unwanted interfacial reactions in the melt [21, 22].

Conversely, MMCs can be easily fabricated in the solid state using powder metallurgy techniques. Powder metallurgy (P/M) is one of the methods successfully used for the preparation of MMCs with better uniformity in reinforcement distribution. The main advantage of P/M over other methods, is the relatively low processing temperature that avoids undesired reactions in the interface between the matrix and reinforcement [23,24]. Therefore, the aim of the present study is to investigate the effect of volume fraction of the reinforcement on the different mechanical properties of the Al-SiC nanocomposite fabricated by the powder metallurgy technique.

(a) Al powder   (b) SiC nano-powder
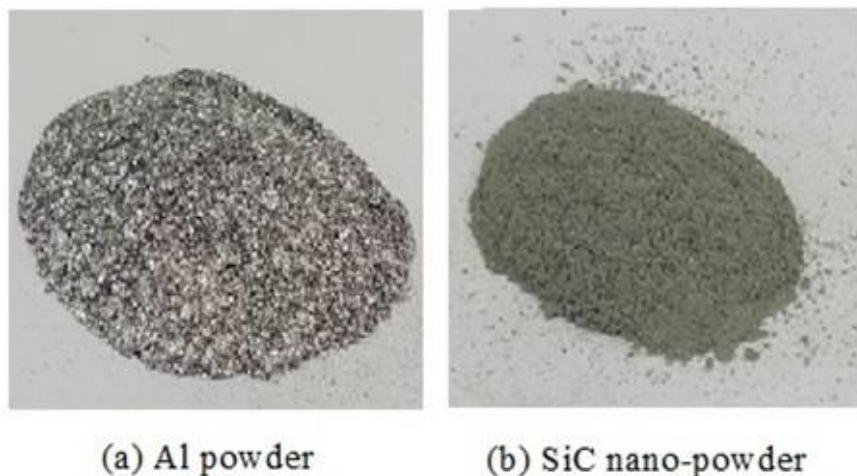
Figure 1. As-received Al powder and SiC nano-powder used in the experiment

Table 1. Properties of raw materials

Properties	Al Powder	SiC Nano Powder
Composition/Particle Size	Al Pure Powder (91% purity)	<100nm
Molecular Weight	26.98g/mol	40.10g/mol
Melting Point	660.37 ºC	2700 ºC
Density	2.7g/ml at 25 ºC	3.22g/ml at 25 ºC

Table 2. Volume fraction of the matrix and reinforcement

Sample	% of Al	% of SiC nanoparticle
S1	90	10
S2	85	15
S3	80	20

2. Materials and experimental procedure

In the present study, the as-received pure Al powders were used as the matrix material and SiC nanoparticles were used as the reinforcement as shown in Figure 1. The properties of the matrix and reinforcement materials are given in Table 1. Aluminium/silicon carbide (Al/SiC) nanocomposite specimens were prepared using conventional powder metallurgy (P/M) route. Three different volume fraction of the reinforcement was used for the study, namely S1, S2 and S3. The composition of these three materials is shown in the Table 2. The desired volume fraction of the reinforcement was measured and mixed properly with the matrix material to achieve the uniformity of the reinforcement particles in the Al matrix. The powder mixture was compacted at room temperature under the compaction load of 200 kN for 20s in a single-die uniaxial hydraulic press (capacity: 300 kN). The schematic diagram of the compaction process is shown in Figure 2.

Once the compaction is done, the green compact specimen was taken out from the mould. The cohesive strength of these green compact specimens was very low and these were very fragile. The green compacts were then sintered at the temperature of 600ºC in a sintering furnace. During sintering, two cycles of heating were applied. In the first cycle, a heating rate of 5ºC/min was maintained to reach the temperature up to 400ºC. Then, 60 minutes holding time was maintained. In the second cycle, the same heating rate was continued to reach the maximum sintering temperature. Once the temperature reached its maximum value, a holding time of 90 minutes was maintained to stabilize the heat on the specimens. The specimens were then cooled in the sintering furnace to reach the normal room temperature. A typical sintering cycle, indicating the heating, holding, and cooling stages are shown in Figure 3. The green compacts and the nanocomposite materials after sintering are shown in Figure 4.

After the sintering process, all the samples were prepared for microstructural characterization and hardness testing. The samples were polished using a polishing machine with 15, 3 and 1 μm diamond particles sequentially to achieve the mirror polish. Microstructural analyses of the samples were carried out using a metallurgical microscope (OLYMPUS BX51M, Made in Japan). Vickers hardness measurements of the samples were carried out using micro-Vickers hardness tester (Wilson Hardness: Model 402 MVD, Made in USA) in accordance with the guidelines in ASTM E384. Vickers hardness (HV) was measured under the test load of 300 gf (2.94 N) along the longitudinal axis of the test specimen. For each specimen, 10 measurements were made with an interval of about 1 mm to avoid any effect by the neighbouring indentations and the average was taken as the Vickers hardness (HV) value.

(a) Schematic diagram of
　　Compaction process

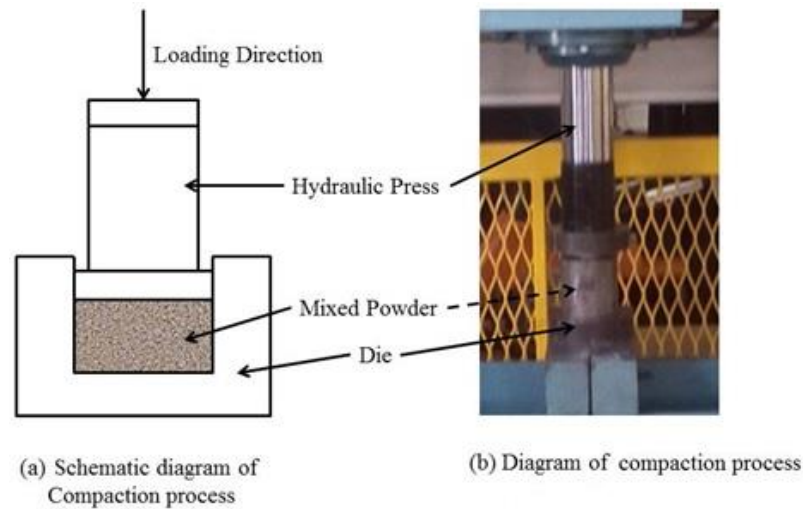(b) Diagram of compaction process
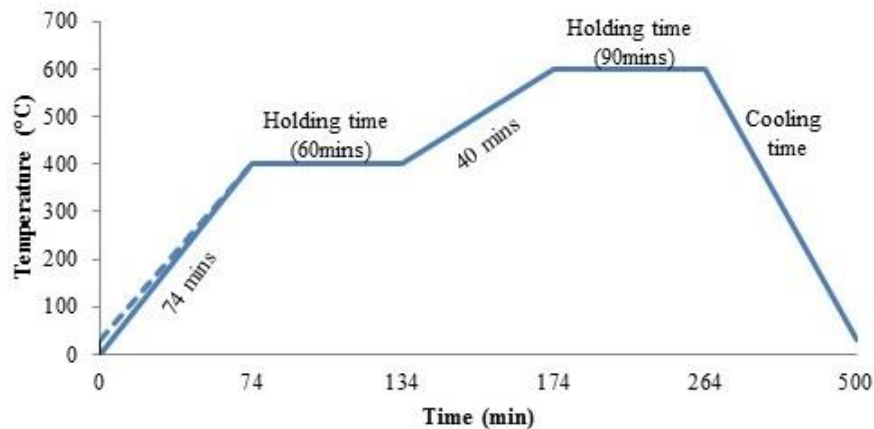
Figure 2. Schematic diagram of the compaction process

Figure 3. Sintering cycle illustrating the heating and cooling rates and the sintering temperature

3. Results and discussion

Figure 5 shows the optical micrograph of Al-SiC nano composites materials with two different volume fraction of the reinforcement (sample S1 and S3). The white area in the micrographs represents the aluminium matrix while the black particles are SiC nanoparticles. The SiC nanoparticles are nearly rectangular shape and are almost uniformly distributed in all the samples. Few agglomeration of the reinforcement nanoparticles was observed in all the cases. Due to the manual mixing of the raw powder materials, the agglomeration of the particles was created. Besides, a small amount of porosity associated with the agglomeration of SiC nanoparticles was also observed in both the cases. The porosity observed around the SiC nanoparticles indicates a weak bonding. This can be attributed to the weak compressibility of the hard SiC particles. When hard and brittle reinforcing particles are used as the reinforcement, these particles do not usually deform plastically, and an elastic-plastic deformation mismatch occurs between the reinforcing particles and the matrix alloy, which results in poor wettability and weak bonding. However, appropriate compaction load and sintering temperature help to reduce the formation of porosity.

　　The density of all the samples was measured before and after the sintering process and the result is exhibited in Figure 6. It is observed that the density of all the samples was higher before sintering and

(a) S1 (90% Al+10% SiC)

(b) S2 (85% Al+15% SiC)

(c) S3 (80% Al+20% SiC)

Green compacts   After sintering
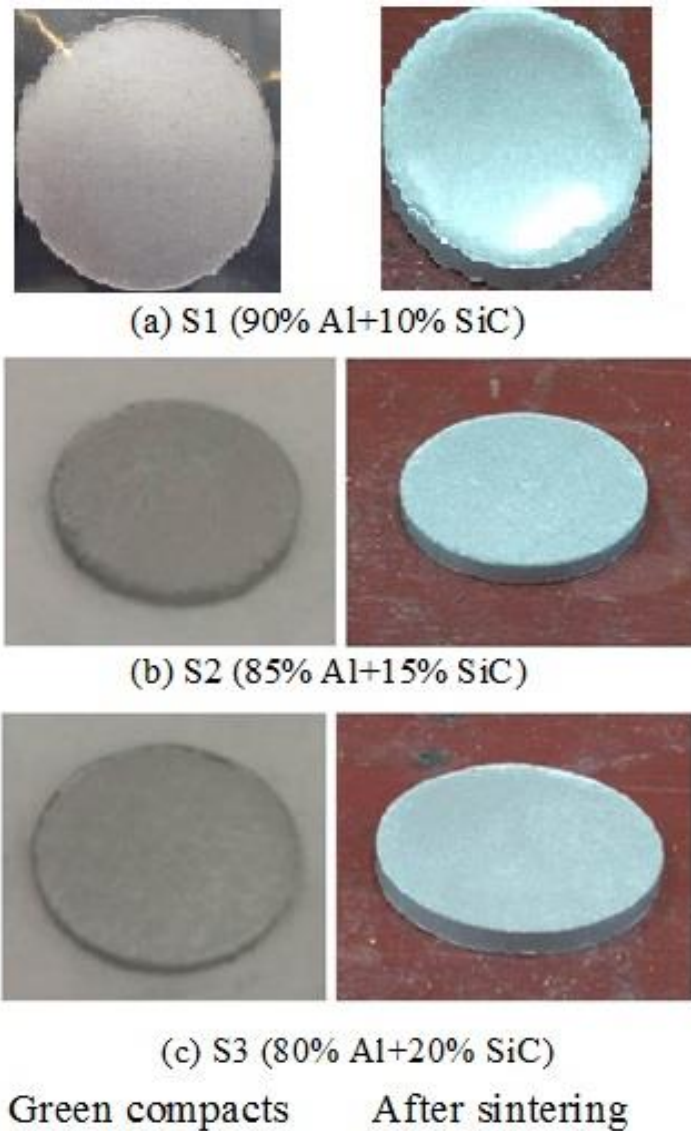
**Figure 4.** Nanocomposite materials after compaction process and sintering

as the sintering is carried out, the density reduced. This occurs because the volume shrinkage took place in the composites at certain higher temperature range, and after that temperature, the volume expanded which is known as swelling. Due to the swelling, the density of the nanocomposite decreased after sintering process. Moreover, it is observed that the sample S1 which is composed of 90% Al and 10 % SiC shows better density value compared to other two types of samples. This material was fabricated with a low volume fraction of the reinforcement, therefore the wettability of the matrix and reinforcement became higher. Thus, produced a less volume and the density increased. Figure 7 shows the results of the hardness of Al-SiC nano composite with different volume fraction of the reinforcement. It is very obvious from the figure that the increase in reinforcement particles increases the hardness of the nanocomposite. It is also observed that sample S3 which is composed of 80% Al and 20% SiC has the highest hardness value as compared to other two compositions. Usually, ceramic particles SiC has higher hardness. Therefore, the addition of higher percentage of this material as a reinforcement increases the total hardness value of the material. This result is in line with the results found by Dutta et al. [25]. The higher compaction load helps to improve the interfacial bonding.

(a) S1 (90% Al+10% SiC)

(b) S3 (80% Al+20% SiC)
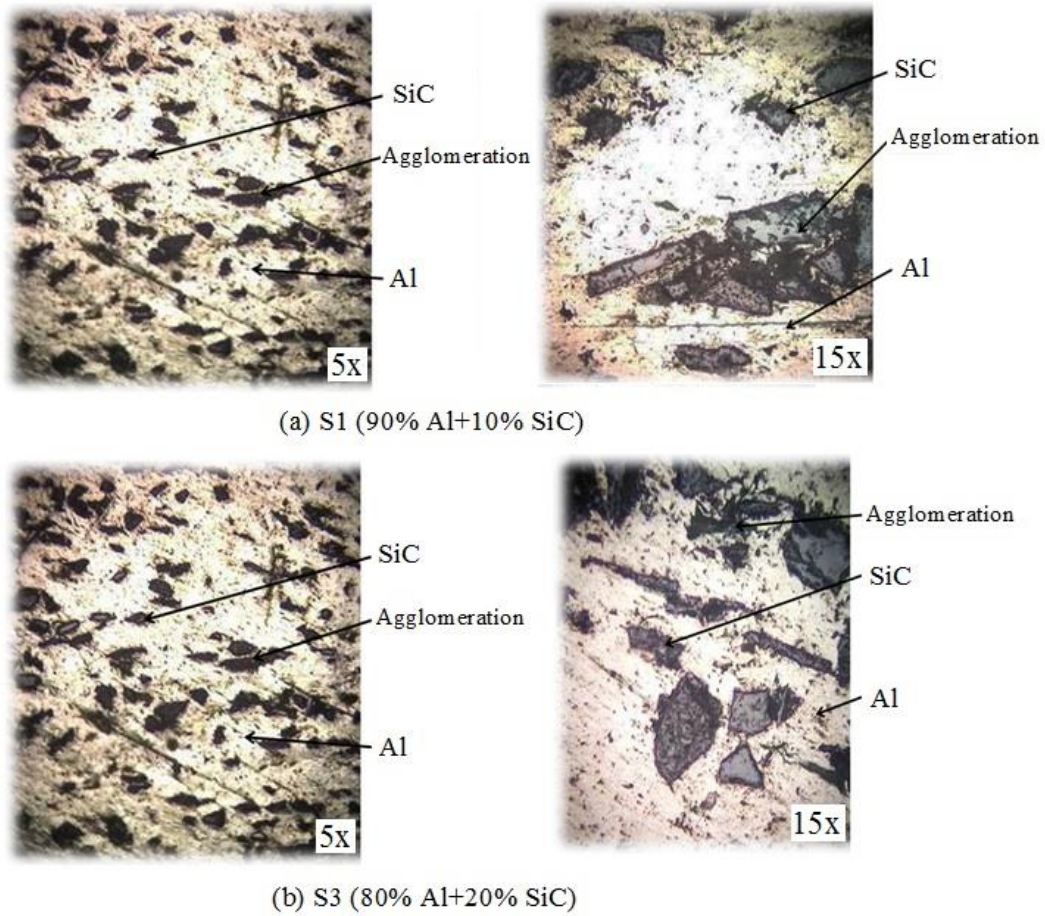
Figure 5. Optical micrograph of Al-SiC nano composite with different volume fraction of reinforcement
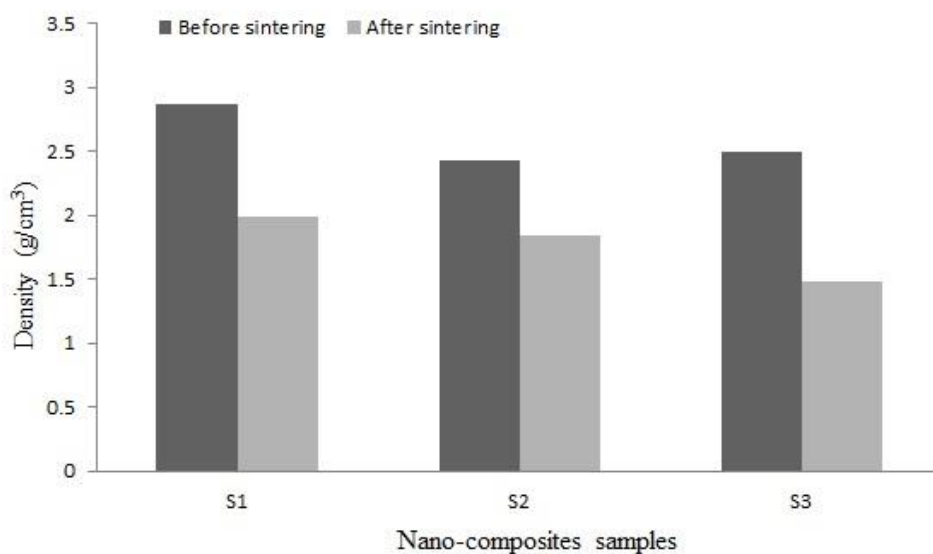
Figure 6. Density of the nanocomposite before and after the sintering
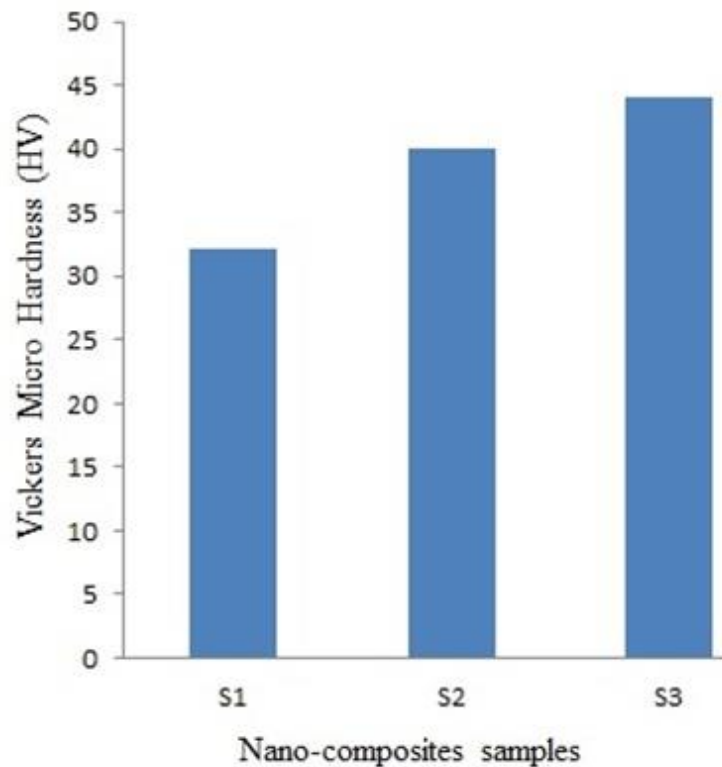
Figure 7. Hardness of the nanocomposites with different volume fraction of the reinforcement

between the matrix and the reinforcing particles. Moreover, the higher sintering temperature reduced the porosity developed in the nanocomposite material. Therefore, the hardness of the nanocomposite increased

4. Conclusions
In this study, the Al-SiC nanocomposite materials were fabricated by a powder metallurgy process and the effect of volume fraction of the reinforcement on the mechanical properties of the Al-SiC nanocomposite were determined. The following conclusions have been made:

1   The density of the nanocomposite decreased after sintering as the vacancies were formed inside the specimens and the volume of the nanocomposite increased. However, the density of the nanocomposite fabricated with 90% Al and 10% SiC was found higher than that of the other two compositions due to the good wettability between the matrix and the reinforcement materials.
2   The higher volume fraction of the reinforcing particles provides better hardness in the composite. The microstructural homogeneity was also observed in the composite with a higher volume fraction of the reinforcement.
3   The Al-SiC nanocomposite fabricated with 80% Al and 20% SiC (S3) exhibited better mechanical properties as compared to the nanocomposite with the other volume fraction of the reinforcement.

References

[1]   El-Kady O, Fathy A. (2014). Effect of SiC particle size on the physical and mechanical properties of extruded Al matrix nanocomposites. Mater Des;54:348–353.

[2]   Rana RS, Purohit R, Soni VK, Das S. (2015). Development and Wear Analysis of Al- Nano SiC Composite Automotive Cam. Mater Today;2:3586–3592.

[3]   Thakur SK, Tun KS, Gupta M. (2010). Enhancing uniform, nonuniform, and total failure strain of aluminum by using SiC at nanolength scale. J. Eng. Mater. Technol;132:041002-041006.

[4]   Manoharan M, Kamat SV. (1991). On the fracture toughness of particulate reinforced metal-matrix composites. Scripta Metall;25:2121-2125.

[5]   Ma ZY, Liu J, Yao CK. (1991). Fracture mechanism in a SiCw-6061 Al composite. J Mater Sci; 26:1971-1976.

[6]   Srivatsan TS. (1995). Cyclic strain resistance and fracture behaviour of Al_2O_3-particulate-reinforced 2014 aluminium alloy metal-matrix composites. Int J Fatigue;17:183-199.

[7]   Dobrzanski LA, Wlodarczyk A, Adamiak M. (2006). The structure and properties of PM composite materials based on EN AW-2124 aluminum alloy reinforced with the BN or Al2O3 ceramic particles. J Mater Process Technol;175:186-191.

[8]   Unlu BS. (2008). Investigation of tribological and mechanical properties Al_2O_3–SiC reinforced Al composites manufactured by casting or P/M method. Mater Des;29:2002-2008.

[9]   Xiong B, Yan Q, Lu B, Cai C. (2011). Effects of SiC volume fraction and Aluminum particulate size on interfacial reactions in SiC nano-particulate reinforced aluminum matrix composites. J Alloys and Compounds;509:1187-1191.

[10] Llloyd DJ. (1994). Particle reinforced aluminium and magnesium matrix composites. Int Mater Rev;39:1-23

[11] Garcia-Cordovilla C, Louis E, Pamies A, Alonso A, Narciso J. (1993). Proceedings of the 9th International Conference on Composite Materials, ICCM-9, Madrid, edited by A. Miravete;1:787.

[12] Davidson DL. (1991). Metal Matrix Composites: Mechanisms and Properties. edited by Everett RK, Arsenault RJ:223.

[13] Lee HL, Lu WH, Chan S. (1992). Abrasive wear of powder metallurgy Al alloy 6061-SiC particle composites. Wear;159:223–231.

[14] Cerit AA, Karamis MB, Nair F, Yildizli K. (2008). Effect of reinforcement particle size and volume fraction on wear behaviour of metal matrix composites. Tribology in industry;30:31-36

[15] Turner CD, Ashby MF. (1996). The cold isostatic pressing of composite powders—I. Experimental investigations using model powders. Acta Materialia;44:4521–4530.

[16] Iqbal AA, Arai Y, Araki W. (2013). Effect of hybrid reinforcement on crack initiation and early propagation mechanisms in cast metal matrix composites during low cycle fatigue. Mater des;45:241-52.

[17] Iqbal AA, Arai Y, Araki W. (2014). Fatigue crack growth mechanism in cast hybrid metal matrix composite reinforced with SiC particles and Al_2O_3 whiskers. Trans Nonferrous Met Soc China;24:1–13.

[18] Iqbal AA, Arai Y, Araki W. (2013). Effect of reinforcement clustering on crack initiation mechanism in a cast hybrid metal matrix composite during low cycle fatigue. Open journal of composite materials;3:97-106.

[19] Knowles AJ, Jiang X, Galano M, Audebert F. (2014). Microstructure and mechanical properties of 6061 Al alloy based composites with SiC nanoparticles. J Alloys and compounds;615:401-405.

[20] Min KH, Kang SP, Kim DG, Kim YD. (2011). Sintering characteristic of Al_2O_3-reinforced 2xxx series Al composite powders. J alloys and compound;400:150-153.

[21]   Prabhu B, Suryanarayana C, An L, Vaidyanathan R. (2006). Synthesis and characterization of high volume fraction Al–Al$_2$O$_3$ nanocomposite powders by high-energy milling. Mater Sci Eng A;425:192-200.

[22]   O'Donell G, Looney L. (2001). Production of aluminium matrix composite components using conventional PM technology. Mater Sci Eng A;303:292-301.

[23]   Scudino S, Liu G, Prashanth KG, Bartusch B, Surreddi KB, Murty BS, Eckert J. (2009). Mechanical properties of Al-based metal matrix composites reinforced with Zr-based glassy particles produced by powder metallurgy. Acta Mater;57:2029-2039.

[24]   Miracle DB. (2005). Metal matrix composites – from science to technological significance. Compos Sci Technol;65:2526–2540.

[25]   Dutta G, Bose D. (2012). Int J Emerg Technol Adv Eng;2:121-123.